Visualization of distributed source solutions in electrophysiology: Examples from MEG

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1 Introduction

Thanks to improvements in measurement accuracy and the development of sophisticate analysis tools it is now almost routine to scan through the brain volume for activations relating to specific tasks or states. Electrophysiological data specifically can be used to obtain continuous estimates of the current density vector in the brain. In the case of EEG and especially MEG such estimates extend over much of the brain volume and surface and over many timeslices. Even if the directional information is ignored the analysis produces a 4D set of data. In recent years we have extended our magnetic field tomography (MFT) [1] analysis to single trials [2] and even the analysis of brain activations following continuous audio-visual stimulation [3]. As a result a huge set of solutions is produced which must be further processed. To achieve this we have followed a twin approach. Objective methods relying on robust statistics provide the main way of reducing the information and squeezing out what is salient from this mass of data. We nevertheless believe that an expert eye should be allowed to make a contribution before the statistical bulldoze levels much of the details down. Effective visualization tools are therefore needed for user defined displays of the activity in the background of relevant anatomy at time periods where significant events are expected. In this paper we review the display tools we have developed in the last few years under the IDL computing environment from Research Systems, Inc. These tools are extensively used both for early user guided exploratory inspection of MFT solutions and for displaying the final statistical measures. We have avoided the trend of restricting the solutions to the cortical surface, with direction along the local normal [4]. The seemingly plausible assumptions underlying these constraints have rarely been tested. The static black and white images in this paper provide some evidence for the utility of the tools, although to appreciate their full power color, interactive manipulation and animation are important. We will demonstrate the visualization task with MFT solutions extracted from MEG measurements (CTF, Omega 151 channel whole head system). For consistency we will use data elicited by stimulation of the left median nerve at the wrist.

2 Methods and examples

2.1 Coregistration and universal alignment

Both 2D and 3D analysis project the current distributions onto anatomical MRI data. For this purpose the headshape of the subject is digitized using a Polhemus stylus device. 10000 Points are collected including the three loci where head location coils (HLC) are firmly attached to the head. Dedicated software is used to coregister this headshape to the contour of the head extracted from the anatomical MRI. As a result the coordinates of the three HLCs are available in the coordinate system used for storing the volumetric MRI information of the subject. A new headshape is obtained before each experiment or during the experiment if for some reason the HLCs are displaced. During each experiment the HLCs are activated and the resulting MEG signal is used to identify their coordinates relative to the sensors. Two such recordings are made for each run, one immediately before and one immediately after the data collection. This allows us to place the MEG sensors relative to the head in the MRI defined coordinate system while providing some measure of head movement during the run. All MFT computations are performed in the same MRI based coordinate system. We can therefore express all MFT solutions for experiments performed with the same subject to the same source space, and hence use identical alignment for each of these solutions to the MRI defined anatomy of the subject. For each experiment some anatomical features are of special interest. Line outlines are then drawn once and used in the displays. In the examples that follow with left median nerve stimulation we have marked the central sulcus outline.

2.2 2D Approach

The integral of activity over a thin slab around a coregistered anatomical MRI slice is our basic two-dimensional display element (B2DE). The current distribution is displayed in some detail over space and time, by arranging B2DEs in a regular matrix with columns containing time-coincident slices cut along a given direction and advancing in time (latency) from left to right. Other B2DE arrangements are also available to emphasize different aspects of the solutions, for example displays of the same solution in two or three perpendicular views.

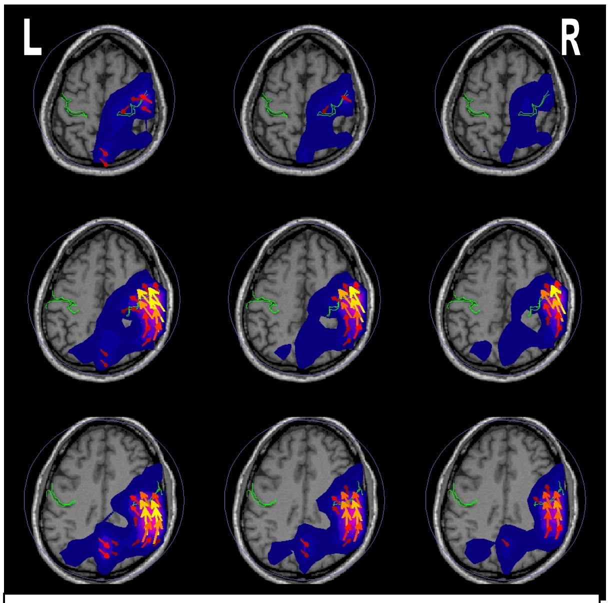

Figure 1. *Three slices of B2DEs, 22.4-28.8ms after stimulus onset. Locally applied Threshold: Vector 25%, Contour 10%.*

Figure 1 shows such a display using three B2DEs for three timeslices. We have deliberately used a very low threshold to emphasize the 3D-vector field nature of the MFT solutions. In figure 2 a more reasonable threshold is used to follow the activity in one level from 19.2 to 28.8 ms after stimulation.

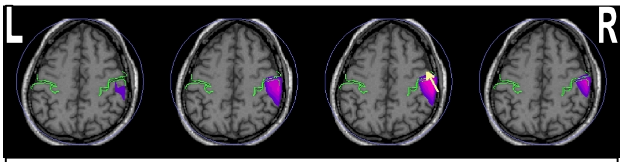

Figure 2. *Slice of max. activation from 19.2-28.8ms Threshold: Vector 99%, Contour 55%.*

2.2.1 Normalization, threshold and ROIs

MEG has a large dynamic range, which is rarely exploited. Four normalization types are supported, each emphasizing best a different aspect of the solution in the available dynamic range. These are, single image and single timeslice normalization, normalization of all displayed timeslices and normalization of the whole recorded dataset. The vector properties or local power can be simultaneously displayed by showing an arrow map of the projection of the current density onto the displayed slice together with the contour plot of the power or current density modulus (square root of power). Directional or local sensitivity can be enhanced by choosing to display the activity along a given direction or within a given region of interest (ROI), as shown in Figure 3. For all these displays separate thresholds are provided for the vector (arrow maps) and the scalar (contour plots) quantities.

2.2.2 Activation curves

In many applications one is interested in identifying ROIs where activity is significant and following the activity in each ROI in time for different conditions. Activation curves are ideal for this purpose. We compute an activation curve for a given ROI by integrating the power, current density modulus or the projection of the current density vector along the direction prevailing at the peak or some predefined latency. These activation curves can be generated within the 2D-display environment or using separate software dedicated to this task. Figure 4 shows an example of directional curves, defined for the ROI displayed in Figure 3.

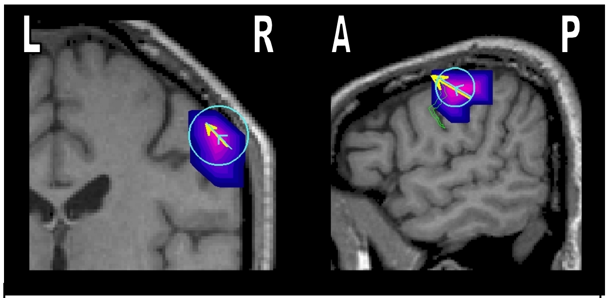

Figure 3. *Two perpendicular MRI slices with the same activation, confined within a predefined ROI. Threshold: Vector 99%, Contour 10%.*

2.3 3D approach

The 2D displays fail to capture the relationship between features in the spatiotemporal distribution of activity and cortical surface topography. We have therefore recently developed full three dimensional displays emphasizing views of activity on the cortical surface which vividly express the relationship of surface topography and function, as well as making interactions between areas on the cortical mantle evident.

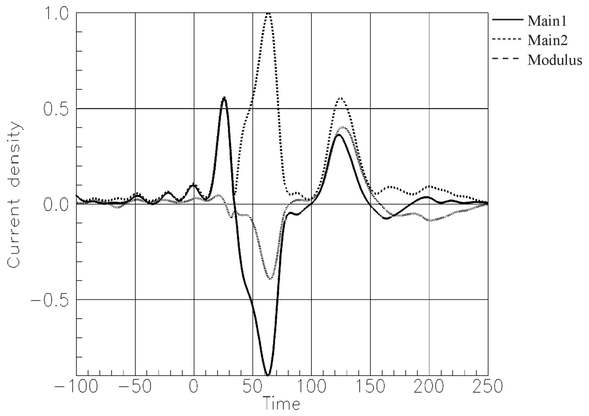

Figure 4. *Activation curve of the S1-ROI shown in fig. 3 over time. Left median nerve stimulation. Main1: Direction along the arrow shown in fig. 3. Main2: Direction perpendicular to main1 and radial direction.*

2.3.1 Brain segmentation

For the three dimensional analysis the brain is segmented, using a morphology based approach similar to the approaches described in [4], [5], and [6]. The first step in the extraction of the cortical surface is based on gray level thresholding, beginning with a 3D region growing operation around a user-selected seed. The dilation, erosion and filling in operations that follow are performed with user defined thresholds. The segmented volume is saved for further use with functional data.

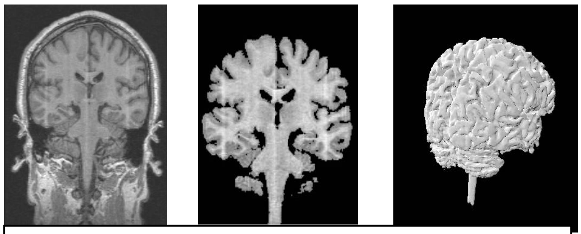

Figure 5. *Original MRI slice, segmented slice and whole segmentation result.*

The brain boundary is extracted from this volume as an isosurface, characterized by a set of vertices and the local normals. This semi-automatic approach takes less than one hour on a modern PC for our typical MRI data set (16MB of data for T1 weighted, 1x1x1 mm voxels in a 256x256x256 matrix).

2.3.2 Representing function on the cortex

The MFT solutions are computed within the entire source space in the nodes of a grid covering the brain and cerebellum. From this volume data the activations at the nodes of the segmented cortical surface are computed using the MFT values at the grid points nearby. Some user control is allowed to fix the precise neighborhood rule and extent of cortical depth to consider. Once the neighbors of a point on the cortex are known, the activation value at that point is calculated as a weighted sum.

For the actual display, a part of the color scale is reserved for gray scale representation of the anatomical volume. The interpolated activation values are smoothed and histogram equalized for mapping to the remaining available color scale.

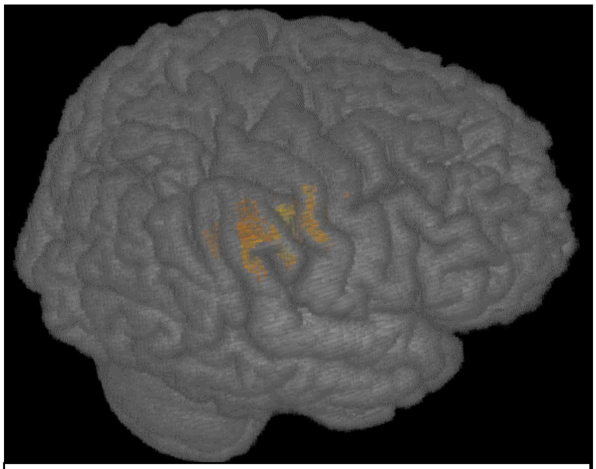

Figure 6. *Modulus of current density on the right cortical surface 25.6ms after stimulus onset. Threshold: 50%.*

The color code is used to display either the modulus (Figure 6) or the direction of current flow relative to the local cortical surface normal (Figure 7). Similar options regarding normalization of the displays are available as for the 2D case.

Since volume rendering is a time consuming operation, the images are first produced with a coarse resolution and then the quality of the image can be improved either in totality or in a user selected area. The image can be zoomed in or out for ease of manipulation of the viewing parameters. Rotations of the volume can be done around each of the three axes (left to right, anterior-posterior, top to bottom) or freely using the mouse.

3 Discussion

We have developed 2D and 3D displays to gain insight into the wealth of information about cortical function that our MFT analysis has unlocked from the MEG data. Sequences of 2D or 3D images like the ones we have described can be cast into format suitable for animation, and for this purpose usually saved as mpeg movies. The discrete images as well as these movies are a helpful step to set up a proper statistical analysis to identify significant changes in activity between conditions or between baseline and brain activity measurements. Especially our tools allow us to evaluate the regional and directional specificity of the unconstrained solutions. As they allow quick and comfortable browsing through the data, including easy generation of activation curves, they make even the visual analysis of relatively large amounts of data feasible. The final image, Figure 8, summarizes our philosophy: we prefer to contrast minimally constrained solutions to anatomy rather than (possibly prematurely) constraining the solutions to anatomy. Figure 8 shows a 2D view (B2DE) but with activity first passed through the 3D cortical surface filter provided by our segmentation. By displaying such images and contrasting them with the full 3D activations the directional and regional specificity of the unconstrained solutions can be evaluated.

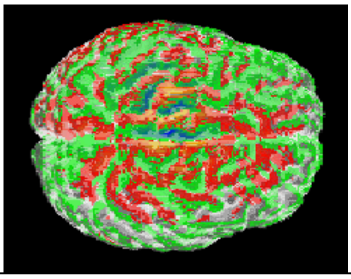

Figure 7. *Directional information: red (blue to green) codes outgoing (incoming) current density direction with respect to local normal.*

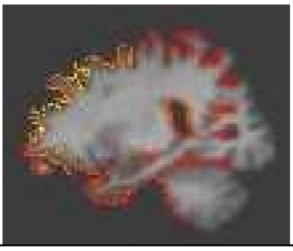

Figure 8. *Slice cut through the volume with activity on the cortical surface highlighted.*

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